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PHASE 2 OF THE ARRAY AUTOMATED ASSEMBLY TASK

FOR THE LOW COST SOLAR ARRAY PROJECT

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Quarterly Report No. 7
April 1, 1979 - June 30, 1979

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Contract No. 954873

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, under NASA Contract NAS7-100 for the U. S. Department of Energy, Division of Solar Energy.

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Westinghouse R&D Center
1310 Beulah Road
Pittsburgh, Pennsylvania 15235

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TECHNICAL CONTENT STATEMENT

NEW TECHNOLOGY

No new technology is reportable for the period covered by this report.

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1. SUMMARY

Two process specifications supplied by other contractors have been tested. The Al Silk Screening Process by Spectrolab resulted in cells comparable to those from sputtered Al. The electroless plating of contacts specification supplied by Motorola could be used only with extensive modification. Several experiments suggest that there is some degradation of the front junction during the Al BSF fabrication. A revised process sequence has been defined which incorporates Al BSF formation. A SAMICS cost analysis of this process yielded a selling price of $0.75/watt peak in 1980$.

2. INTRODUCTION

The major objective of this program is to define and verify a process sequence for the fabrication of solar cell modules from dendritic web silicon. Another objective is the development of key process steps. The process sequence and the individual steps must be amenable to automation and low cost manufacturing methods so that the target selling price of $0.70/watt peak (1980$ in 1986) can be achieved.

Back surface fields (i.e., the pp^+ junction in an n^+pp^+ cell) are incorporated into solar cells to enhance the open circuit voltage and the short circuit current and thus improve the efficiency. The back surface field operates by decoupling the high carrier recombination velocity region of the ohmic back surface from the bulk of the cell. The back surface field cells which show the largest V_{oc} enhancement have been prepared by alloying in a deposited Al layer from a deep, (8-10 μm) abrupt p^+ region.

In our studies of the Al BSF's we have selected sputtering as the best technique for depositing the aluminum. The sputtered Al layers are of high purity, very adherent to the Si surface, and when alloyed

in, they form uniform p^+ layers. Another method for depositing the aluminum is by silk screening an Al paste. This method has the advantage of lower initial capital investment, but the overall cost and reliability must be determined. During this period we tested a Process Specification supplied by Spectrolab which uses an AMPAL aluminum powder. Following this procedure Al layers were screened onto float zone Si wafers and dendritic web silicon strips and alloyed in following their temperature cycle. (The dendrites on the web samples were removed before silk screening.) The cells fabricated in this way were equal in performance to the cells with sputtered Al BSF's. However, in our process sequence, we have retained sputtering as the preferred technique, since special machinery would be required to silk screen between the dendrites. In our process sequence, the dendrites are left on the cells throughout much of the processing to maintain strength and reduce breakage loss.

Our results with all the Al BSF techniques have shown V_{oc} enhancement up to 0.585V. However, the physical parameters of the BSF (e.g. p^+ width, surface concentration, junction gradient etc.) indicate that V_{oc} should be at least 20 mV higher. It was postulated that during the BSF formation the front junction, which also effects the V_{oc}, might be degraded. Several experiments showed that some front surface protection was required, with the best results occurring when the phosphorous glass was left on the n^+ surface.

A totally plated contact system would conceivably be less expensive than an evaporated and electroplated system. Using a Process Specification supplied by Motorola, we attempted to use this technique in our process sequence. The process involves the electroless deposition of Pd and Ni followed by the build up of a conductive layer (solder in the Motorola process). Several tests showed that it was necessary to modify the process significantly since the acidic rinses attacked the AR coating. (They would not attack the Si_3N_4 coating used by Motorola.) Even with these modifications, the cell performance was significantly lower than cells produced by the baseline evaporated Ti Pd electroplated Ag system. Based on these data, it was decided that this process was not immediately applicable to our process sequence.

The ultrasonic bonding of interconnect straps has several advantages in that no corrosive fluxes are used and there is no excessive build-up of metal in the contact area. A matrix has been defined where for given values of power, time and force, good bonds are achieved. These matrices have been developed for copper and aluminum interconnect straps to silver and copper contacts. A similar schedule has been studied for Al and Cu straps to the Al back contact, but the results are less reproducible. Several small mechanical panels have been fabricated using ultrasonic bonding.

The process sequence previously defined has been revised by using an Al BSF to replace the boron BSF. This simplified several of the sub-processes and decreased the total commodities cost. Using SAMICS methodology the selling price of a dendritic web solar panel was $0.75/watt peak (1980$ in 1986).

3. TECHNICAL RESULTS

3.1 Aluminum Back Surface Field (BSF) Studies

3.1.1 Introduction

The high-low junction at the back of an $n^{+}p$ cell results in enhanced open circuit voltage and short circuit current. These back surface fields (p^{+} regions) are produced either by a boron diffusion or, preferably, by liquid phase epitaxial growth from Al-Si alloy.

In previous work we have shown that the aluminum used for the Al BSF may be deposited on the silicon surface by either sputtering or a silk screening process. The former, however, is preferred because silk screening the silicon between the dendrities involves complicated equipment. The deposited aluminum is alloyed into the silicon by a short heating cycle of one minute at 850°C. Open circuit voltage enhancement of up to 50 mV is noted after the back surface field preparation with maximum V_{oc}'s on float zone silicon being 0.59V.

During this period, experiments were carried out to verify the Spectrolab Process Sequence using a silk screen Al paste and to investigate possible reasons for the open circuit voltage not exceeding 0.6V.

3.1.2 Silk Screened "AMPAL" Paste

Al BSF cells have been fabricated by alloying in a silk-screened Al paste. The paste was prepared using AMPAL powder* and the Spectralab Process Specification. The paste was applied using a 200 wire/inch stainless steel screen with 0.001" wire (open area of 0.004" x 0.004"). After the Al paste was applied it was dried at 200°C for 15 minutes and then alloyed in an RF heated furnace at 850°C in H_2 or in a resistance heated furnace at 850°C in N_2.

The silk-screened samples did not show any excessive bubbling or lifting of the Al layer during alloying as was noted with the evaporated material and some of the previous samples using other pastes. In both the resistance heated furnace and in the RF furnace, the melted Al on the back surface after alloying was sufficiently unoxidized, so that further metallization was not required to form a back contact. There was, however, some warping of the cell structure after the alloying. This warpage, due to the thick Al, meant the metal must be removed to relieve the stress. In several cases this warpage was sufficiently bad to crack the silicon. This could indicate that large area screen printed devices may be difficult to fabricate by this process due to warpage and breakage.

Table 1 shows the cell data for this experiment. All dendritic web samples were from web crystal W-141-1.4. The first two processses (1 and 2) compare slow cooled and normal cooled web samples alloyed in an RF furnace. The lifetime of the slow cooled material is about double that of the normally cooled, and this effect is mirrored in the short circuit current. The low efficiency of the fast cooled material is due to both the low I_{sc} and fill factor.

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*AMPAL-631 powder - manufactured by Atmomized Metal Powders, Inc., Flemington, NJ 08822.

TABLE 1

CELLS WITH Al BSF PRODUCED BY ALLOYING SILK SCREENED "AMPAL" PASTE

(AM-1; 100 mA/cm^2; AR coated; Web #W-1414-1.4)

Process	V_{oc}(V)	$I_{sc}(\frac{mA}{cm^2})$	FF	η(%)	τ_{OCD}(μsec)	p^+ width (μm)
1. Web - RF Fce 850°C - Normal cool	.559	30.8	.69	11.9	2.5	2
2. Web - RF Fce 850°C - Slow Cool	.558	33.8	.73	13.9	5	4
3. Web Sputtered Al 850°C - Slow Cool	.565	34.7	.70	13.6	4	4
4. Web - Boron BSF	.569	32.6	.74	13.8	6	—
5. FZ Si - RF Fce 850°C - Slow cool	.540	33.3	.73	13.4	13	5
6. FZ Si - RF Fce Sputtered Al 850° - Slow Cool	.572	34.8	.72	14.5	20	6

Process 3 samples are controls and are fabricated on the same web crystal with the Al BSF produced by alloying a sputtered Al layer. Process 4 samples are also controls and are boron BSF cells produced by the standard qualification process. Process 2 compares favorably with these control samples.

Process 5 samples are fabricated on float zone Si with the BSF produced by alloying in the silk screened AMPAL paste. These results are to be compared with Process 6, which are FZ silicon cells with alloyed in sputtered Al layers. The loss of lifetime in the silk-screened FZ cell (20 μsec to 13 μsec) may be due to some lifetime killing impurity, since all control samples were reacted at the same time as the experimental samples. The effect of the lifetime loss is noted in both I_{sc} and η for the cells in Process 6.

The data indicate that Al BSF cells can be fabricated using silk screened "AMPAL" paste which are essentially equal to the sputtered Al process.

The open circuit voltages noted in Table 1 are lower than that generally reported for Al back surface fields. This lower value cannot generally be explained in terms of a too shallow p^+ layer.

The measured values of the OCD lifetime and the short circuit current, while not as high as expected for an Al BSF, do indicate an operational back surface field. However, the open circuit voltage is also controlled by the front junction, and it is possible that the front junction was degraded due to the fabrication of the Al BSF.

3.1.3 Front Surface Protection

As noted in the previous section, the enhancement of the open circuit voltage of Al BSF cells was less than expected for the noted cell lifetime and p^+ profile.

In an effort to determine if a small amount of aluminum was contaminating the front junction, either during aluminum application or alloying, several experiments were carried out in which the front surface

was protected, and an experiment in which the n^+ layer was diffused in after the p^+ layer was prepared. These results, as well as the experimental conditions are given in Table 2. The data given are the averages of 8 - 16 cells for each treatment. In all cases the p^+ layer was prepared by alloying in a silk-screened layer of AMPAL #631 paste (as described earlier). The penetration of the p^+ layer was 6 - 8 μm.

The samples, in which the phosphorous glass diffusant source was in place during the alloying, gave uniformly superior results. Treatment #3 (n^+ layer formed after p^+ layer) was the poorest and these results may be due to a grading of the p^+ junction during the 850°C diffusion to for the n^+ layer.

Treatment #1 (top surface protected by SiO_2) produced cells which were also considerably poorer than the cells fabricated with the phosphorous glass protection.

Although not conclusive, these data do suggest that there is some effect on the top surface (i.e. top n^+p junction) during the BSF formation.

It should also be noted that even in the best case (Treatment #2) where the cells have a 24 μsec lifetime and a p^+ layer of 5 μm, the V_{oc} is relatively low for an Al BSF.

This phase of the program is now being discontinued. We will continue to study possible reasons for the lack of V_{oc} enhancement on internal funded programs.

3.2 Electroless Plated Contacts

A total plated system for contacts may have certain cost-benefits, specifically, lower capital costs as compared to an evaporated (or sputtered) plus plated system.

In the last quarterly report on this program, initial experiments were carried out using the Process Specification supplied by Motorola. In these first experiments it was found necessary to modify the Motorola process since the etches and rinses called for in the specification used HF which attached the antireflection coating. (This is not a problem in

TABLE 2

Al BACK SURFACE FIELD RESULTS (AVERAGE VALUES)
(Silk Screened AMPAL - #631 - 850°C Drive In)

	Treatment	I_{sc}(mA)	V_{oc}(V)	FF	η(%)	τ_{OCD}(μsec)
1.	SiO_2 on n^+ side	30.96	.562	.723	13.3	16
2.	Phos. glass on n^+ side	31.67	.572	.746	14.3	24
3.	p^+ layer formed before n^+ layer	30.96	.540	.730	12.9	12

Notes

Treatment 1 - Phos. glass removed after $POCl_3$ diffusion; SiO_2 applied to one n^+ side to protect surface from Al. Al driven through n^+ layer.

Treatment 2 - Phos. glass removed from one side; left on one n^+ side to protect surface from Al. Al driven through cleaned n^+ layer.

Treatment 3 - Al driven into p crystal; excess Al removed and n^+ diffusion carried out. p^+ surface recontacted with Ti Pd Ag.

Measured at AM-1; 91.6 MW/cm^2 - AR coated

the Motorola process sequence since they use silicon nitride as an AR coating which is not easily attached by the rinses. The AR coating in our process sequence is a mixed TiO_2/SiO_2 system which is attached by HF). It, therefore, became necessary to reduce the rinsing time in the HF solutions to preserve the integrity of the AR coating.

In these initial experiments, the yield of testable cells was small. These data, however, indicated that there was some degradation in cell parameters using plated contacts as compared to cells on the same web crystal with normal processing. However, in view of the limited data, the experiment was repeated with a larger number of samples.

In this period we have completed a test run where 30 cells (all from the same web crystal) were processed through this modified procedure (including an electroplated Ag top metal replacing the solder dip). Before the initial plating, the cells had an AR coat with the contact grid etched to the Si.

The data on these cells are given in Table 3. Only 15 cells survived to the testing stage. The main loss mechanism was a slight attack of the AR coating by the Pd plating solution with subsequent nucleation of Pd on areas other than the cell grid structure. During the second plating, the nickel plated over much of the cell surface, apparently using the Pd nuclei as starting points.

In the table, the cells with poor properties (31, 32, 52) have very high series resistances, perhaps due to a spotty removal of the AR coating. In general, the efficiency of the best cells was 2.5-3% (absolute) lower than the standard processed cells. Both the I_{SC} and V_{OC} of the test cells were lower than those for the standard cell which is consistent with the much lower lifetime measured. Some decrease in the I_{SC} may also be due to an attack by the solutions in the AR coating which would make it less effective, i.e., lower enhancement. After these measurements, selected cells were sintered for 15 minutes at 425°C. There was no systematic improvement.

TABLE 3

Parameters of Cells Fabricated Using

Modified Electroless Plating for Contacts (1)(2)

Cell #	I_{SC} (mA)	V_{OC} (V)	FF	EFF (%)	τ_{OCD} (μsec)
11	27.9	.515	.719	10.8	1.7
12	28.1	.510	.721	10.9	1.6
21	26.8	.514	.711	10.4	1.8
22	26.9	.513	.718	10.5	2.1
31	19.3	.483	.365	3.6	.9
32	22.6	.501	.363	4.4	2.0
41	29.2	.502	.697	10.8	1.2
42	28.7	.502	.672	10.2	1.2
52	18.5	.479	.351	3.3	1.8
61	29.0	.508	.721	11.2	1.8
62	28.6	.500	.707	10.7	1.8
71	27.8	.496	.629	9.2	3.1
72	28.6	.508	.704	10.8	2.9
81	26.0	.480	.661	8.7	1.0
82	27.2	.501	.704	10.2	1.0
STD (3)	29.8	.556	.740	13.3	12.0

1) AM-1 Illumination - 91.6 watts/cm^2, AR coated.

2) All cells fabricated from same web crystal.

3) These are the parameters of cells fabricated from the same web crystal but with evaporated Ti-Pd-Ag contacts.

From the results of these and earlier tests we conclude that the Motorola process specification is not immediately transferable to the process sequence we use. It is also concluded that substantial effort would be required to make use of this process specification.

3.3 Ultrasonic Bonding of Cell Interconnections

3.3.1 Introduction

In the process sequence we have defined, the cell interconnections are made by ultrasonic bonding. This technique has several advantages. First, no corrosive acids or fluxes are used in the process and therefore no clean-up is required. Secondly, there is no excessive metal build-up on the top surface of the cell which simplifies module fabrication.

In earlier reports, a matrix of power-force-and time was given for bonding copper straps to plated silver and nickel straps to plated silver. These tests have been continued to study the bonding to aluminum. This will be required for the Al BSF cells.

3.3.2 Ultrasonic Bonding to Aluminum

Bonding experiments have been carried out to show the feasibility of ultrasonic bonding to Al. In general, it is possible to produce strong bonds to sputtered and alloyed in Al although the reproducibility is not as good as with the silver contact. Pull strength data have been obtained for copper, nickel, and aluminum ribbon leads bonded to sputtered and alloyed aluminum. The data is shown in Table 4.

Since the demonstration modules will be fabricated using Al back surface fields, contacting to Al is a necessity. The reproducibility problems are being studied further.

3.3.3 Module Fabrication Using Ultrasonic Bonding

A test has been designed to simulate the method chosen to interconnect a dendritic web solar cell module. As outlined in our

TABLE 4

ULTRASONIC BONDING TO ALUMINUM

Interconnect Strap	# of Bonds	Av. Strength (grams)	Std. Derivation
Copper	8	88	54
Nickel	8	30	10
Aluminum	9	100	85

process sequence the test cells were embedded in a thin coating of GE RTV 615 on a glass plate. Ribbon leads were then ultrasonically bonded to the Ti/Pd/plated Ag back surface. (This contact system was used for the test due to the reproducibility problem with the Al bonding, which could bias the experiment.) 90% of the bonds were good. Pull test data are shown in Table 5.

TABLE 5

PULL TEST DATA - 2 mil Nickel Ribbon - 14 Bonds Tested

Bond parameters	- Force 24 oz. Power 25W Bond time 1.2 sec
Average pull strength	- 153 grams
Maximum pull strength	- 261 grams
Minimum pull strength	- 9 grams
Std. Deviation	70 grams

These data show bond strengths equivalent to or better than those previously reported for cells not embedded in RTV. The next test was similar, except that ribbon leads were first bonded to the sun side of the cells before embedding in RTV. This test was designed to provide a more complete simulation of an actual interconnected module. The concern here was that the ribbon lead thickness might aggravate the tendency for the cells to crack under the high-point loading required during ultrasonic bonding of the leads to the back side of adjacent cells in the array. The first attempt was not successful because of excessive thickness of the RTV under the embedded cells with the result that many cells were cracked. A second assembly was prepared and extra care was taken to ensure that only the minimum thickness of RTV was present betwee :e cell and glass for proper adhesion ($\sim$ 2 mils). The results of this test were significantly better. It was possible to produce strong bonds to plated Ag using three different metal ribbon leacs (Al, Cu, and Ni) without cracking the cells. The bonds cannot be pull tested because of the short lengths of ribbon extending from the welds. However, a qualitative evaluation of bond strengths indicates that the pull strengths are comparable to those previously tested. Additional tests are planned to further refine our assembly and handling techniques.

In order to interconnect a working cell array on larger plates, additional clearance is needed between the weld tip and the base of the ultrasonic shank. An extended shank (6.587 inches) has been ordered together with a longer weld tip. This assembly will permit the interconnection of cell arrays mounted on plates up to 12 x 12 inches.

3.4 Process Sequence and Cost Analysis

3.4.1 Process Sequence

The process we have defined for dendritic web silicon solar panels was detailed in the first Annual Report on this contract. This pr ess utilized a back surface produced by boron diffusion and required, in addition to the boron diffusion, several oxide masking steps. It has been shown that back surface fields produced by Al are more

effective, and much of our experimental effort this year has emphasized the production of Al BSF, and this process has now been inserted into the process sequence.

The revised process sequence used now is as follows:

- As received web cleaned with an organic followed by plasma cleaning.
- Front junction prepared by $POCl_3$ diffusion.
- Phosphorous glass cleaned from one side of web and a 10 μm layer of Al sputtered on the cleaned surface.
- Al driven in through the n^+ layer.
- All oxides removed.
- Web length dipped in AR solution and baked.
- Web length dipped in PR and baked.
- Grid pattern exposed; PR developed and AR etched to open grid.
- Ti/Pd evaporated on entire web and excess metal rejected with PR stripper.
- Conductive layer built up with silver (copper) electroplating.
- Cell structure broken from matrix using laser scribing.
- After testing, interconnect straps bonded to front contacts (ultrasonic bonding).
- Cells mounted face down on glass with adhesive.
- Back interconnects made (ultrasonic bonding).
- Substrate attached using adhesive.

3.4.2 Cells Produced by Process Sequence

This process has been used in fabricating a large number of cells. An efficiency distribution of float zone Si cells and web cells are shown in Figs. 1 and 2. Figure 1 which shows the float zone Si distribution which have an average of 14.5% with a maximum efficiency of 15.5%. These data indicate that the described process is capable of producing high efficiency cells. Figure 2, which shows the efficiency distribution for the web silicon cells, reveals an average efficiency of about 13.5%. However, the maximum efficiency is also 15.5% which indicates that dendritic web silicon is capable of cells as efficient as those prepared from float zone silicon.

3.4.3 SAMICS Cost Analysis

The cost factors of the various sub-processes have been analyzed see Sec. 3.4.4 and transferred to Format A's. The total cost of the process has been determined using Release III of the SAMICS program.

This calculation was made under the following assumptions:

25 MW/yr production.

5000 cm^2/min web input; 345 days/yr.
Operation with 3 shifts.
Web is 5 cm wide.

Process produces 12% panels.

85% yield of cells.

95% yield of panels.

With these inputs, a selling price of $.75/watt peak was obtained (1980$).

A breakdown of the contribution of the various sub-processes to this selling price is shown in Table 6.

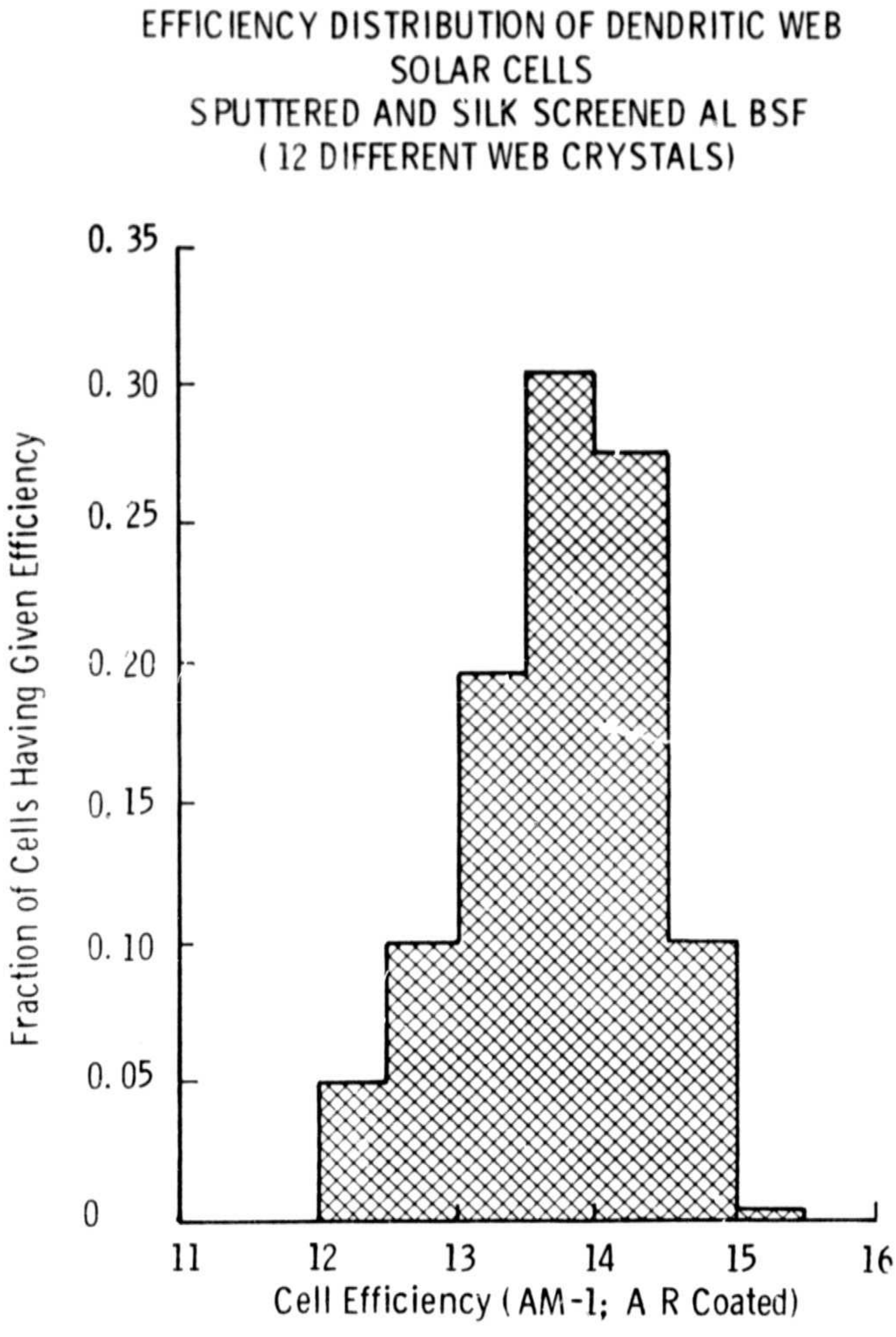


Fig. 1 Efficiency Distribution of Float Zone Silicon Solar Cells Sputtered and Silk Screened AL BSF

Curve 717998-A

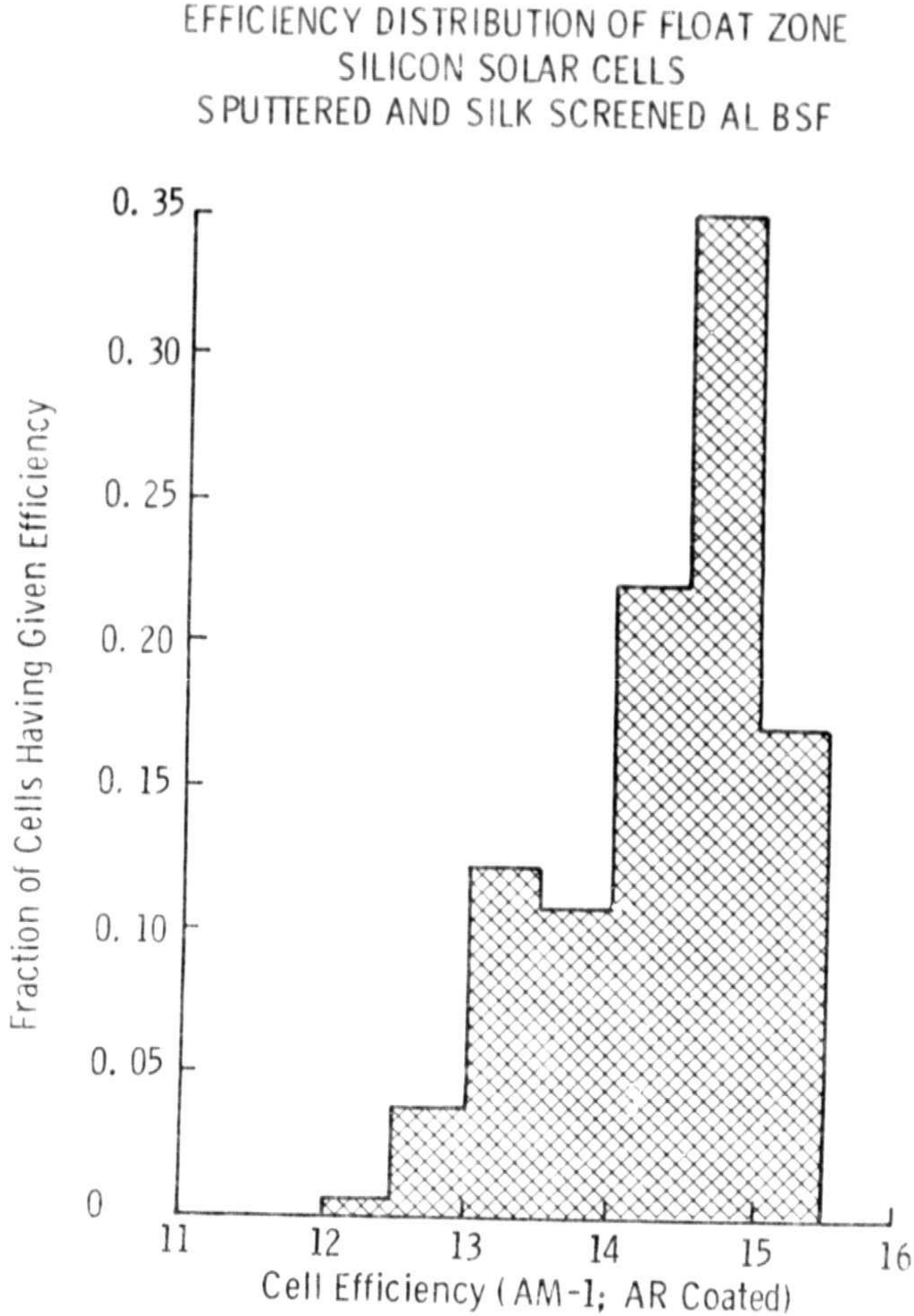
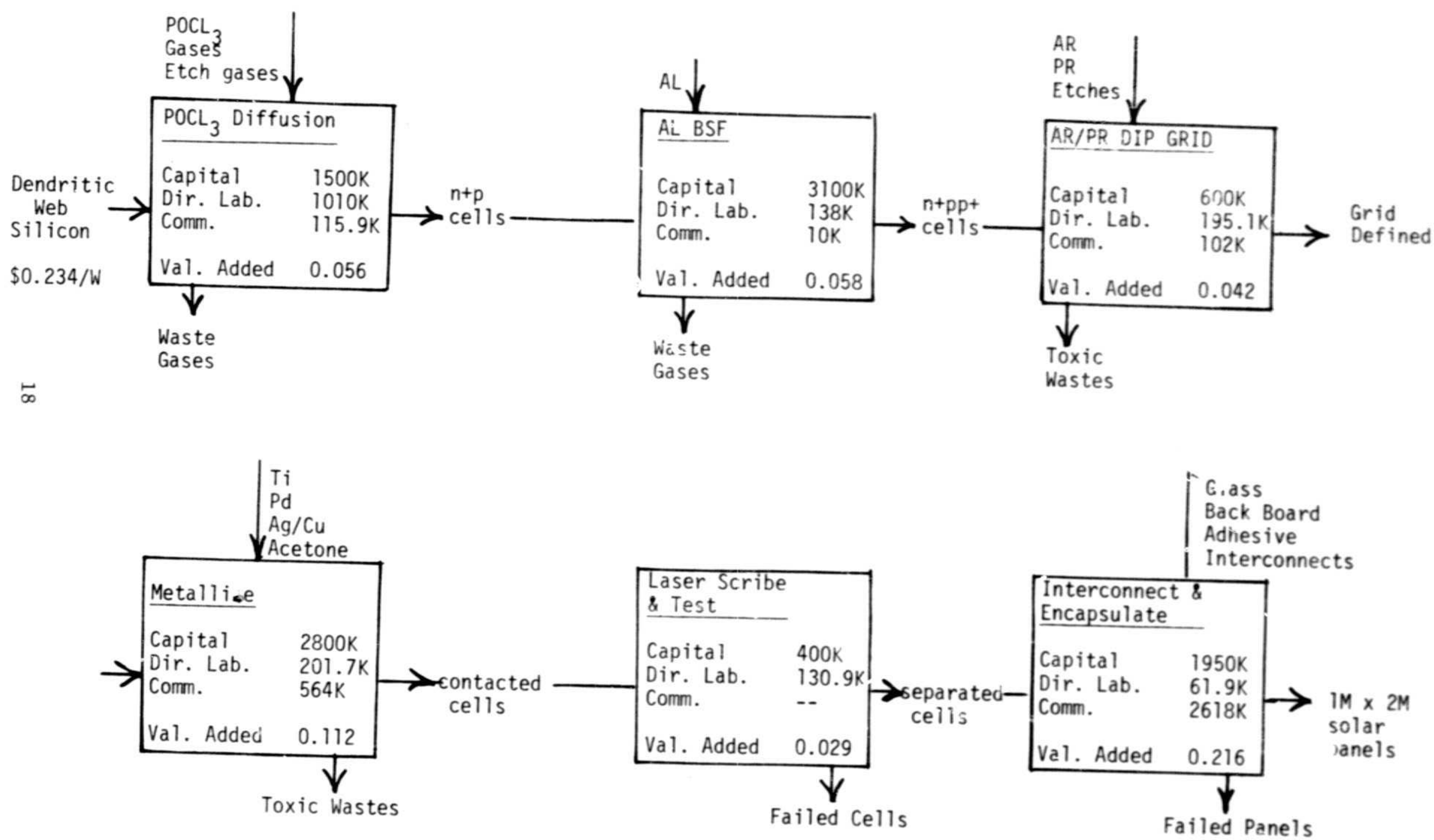


Fig. 2 Efficiency Distribution of Dendritic Web Solar Cells Sputtered and Silk Screened AL BSF (12 different web crystals)

TABLE 6

Ⓦ PROCESS SEQUENCE COSTS (ALL 1980$)



3.4.4 Costs Used in Format A's

The Format A's require among other inputs estimation of the costs of commodities and capital equipment. To obtain these factors, we requested budgetary estimates from a number of vendors for equipment sufficiently large for a 25 MW/yr production line. In addition, cost breaks obtainable on larger volume purchases of commodities not listed in the SAMICS Cost Accounting Catalog have been obtained.

4. CONCLUSIONS

Operational back surface fields have been produced using aluminum p^+ layers. Several tests have shown that some of the problems in achieving an even higher V_{oc} may be due to the Al BSF formation process degrading the front junction.

The Spectrolab Process Specification for silk screened Al back surface fields has been tested. The Al BSF cells produced in this way are essentially equal to those produced using sputtered Al layers.

The Motorola Process Specification for total plated contacts has been tested.

The specification required considerable modification due to the attack on the antireflection coating by the acidic rinses. With these modifications, cells were produced and tested. The average efficiency of the total plated cells was about 2 - 3% (absolute) lower than cells produced using the standard process.

Ultrasonic bonding tests have been continued and a mechanical panel has been fabricated using ultrasonic techniques. Strong, reliable bonds have been achieved between Al and Cu interconnect straps and Ag, Cu and Al contact metals. The reproducibility of bonds to the Al contact needs to be improved.

A revised process sequence has been defined which includes an Al back surface field formation. A cost analysis of this sequence shows a selling price of $0.75/watt peak in 1980 dollars.

5. PROGRAM STATUS

5.1 Present Status

The Al BSF work on this program has been discontinued, however, this work is being continued under an internally funded program.

The study of the total electroless plated contacted system has been finished. Our results indicate that a significant modification would be required in the process sequence to utilize this technique. Even with these modifications it is not certain this method would produce cells equal to the standard process.

Strong reliable bonds between contact metals and interconnect straps have been achieved. However, the reproducibility of bonds to the Al contact metal must be improved.

The basic SAMICS costing has been completed and the Format A's have been submitted to JPL.

5.2 Future Work

Experimental work will concentrate on fabricating demonstration modules according to the process sequence.

A number of iterations will be carried out on the basic SAMICS costing. These will be carried out to point out cost drivers and possible process sequence improvements.

6. ACKNOWLEDGEMENTS

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